Renewable and Sustainable Energy Reviews 15 (2011) 1791–1800

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Potential non-edible oil resources as biodiesel feedstock: An Indian perspective

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ARTICLE INFO

Article history:
Received 13 June 2010
Accepted 10 November 2010

Keywords:
Bioenergy
Sustainable
Biofuel
Biodiesel
Feedstocks
Oil crops

ABSTRACT

As the world confronts a reported food shortage and rising fuel prices, scientists around the globe are scrambling to develop biofuel feedstocks that would not divert food crops to energy. It is apparent that the demand for biodiesel is expected to increase in near future and although many edible oils might be the cheapest feedstock for biofuel production. But it may not be sustainable source to meet this increasing demand. This justifies the need to use non-edible oil seeds that can be the reliable sustainable feedstock for biofuel production. Furthermore, most of the non-edible seeds bearing trees have the potentials of reclaiming wasteland and does not compete with food crop for limited growing regions. It thus becomes imperative to search for dedicated non-edible feedstocks and their suitability for biodiesel production. This paper attempts to make an assessment of current energy scenario, potential of non-edible oil over edible oils, selected non-edible oil seeds as biodiesel feedstocks, impact of biofuel on environment and future direction. Experimental analysis by different researchers on these non-edible oils showed their great potential as feedstocks for biodiesel production. This paper also reviews the biology, distribution and chemistry of selected non-edible oil seeds plants.

Contents

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doi:10.1016/j.rser.2010.11.020

1. Introduction

The issues of climate change and energy security have become much higher priorities in modern times and the quest for sustainable energy sources in light of the environmental problems and escalating energy prices has resulted in increase global support of biofuel production as an alternative source of energy in Asian countries. Several alternative technologies are available as a solution to environmental and energy problems: biofuels, plug-in electrics, hybrids, compressed natural gas, or hydrogen-fuelled vehicles. Among these alternative technologies, the use of bioenergy is proving to be particularly attractive and viable and, therefore, is becoming an important consideration [1]. The simplicity of production and use and price advantages, liquid biofuels appear to have a head start in this race [2]. The current energy situation has stimulated active research interest in non-petroleum based, renewable, and non-polluting fuels. The growth of biofuels around the world is spurred largely by energy security and environmental concerns and a wide range of market mechanisms, incentives and subsidies have been put in place to facilitate their growth. Developing countries, apart from these considerations, also view biofuels as a potential means to speed-up rural development and create employment opportunities.

Currently, renewable energy sources signify about 14% of primary-energy consumption in the world, among which biomass being the major contributor (~10%). It is obvious that the growth projections of the biofuel industry are likely to place enormous pressure on the environment and biodiversity in developing regions. At present the global biofuel market utilizes first generation technologies and relies mainly on agricultural food or feed crops for biodiesel feedstock. The primary cost component in biodiesel production process is the vegetable oil and their availability. Soybean and rapeseed are common biodiesel feedstock in USA and Europe. Likewise, palm is being extensively used in South East Asia. It is an estimate that even if all the edible oils are used for biodiesel production, even then they will not be sufficient for meeting fuel demand [3].

According to international energy agency, the scenario of predicted biofuel production in 2030 will increase drastically (Fig. 1). Thus, biofuels from different feedstock are seems to be the only foreseeable alternative sources of energy that can efficiently replace petroleum-based fuels in the long term. According to Fig. 2, the bioenergy supply potential in the world will be 110 EJ/year in 2050 and 22 EJ/year in 2100 [4].

Estimate indicates that biodiesel could represent as much as 20–22% of all on-road diesel used in Brazil, Europe, China and India by the year 2020. Use of biodiesel is catching up all over the world especially in developed countries. Rapid economic growth in China and India would significantly increase world demand for oil. At present, India is producing only 30% of the total petroleum fuels required. India is the fifth largest energy consumer and imported nearly 70% of its crude oil requirement (90 million tonnes) during 2003–2004, which costs about Rs. 80,000 crore every year.

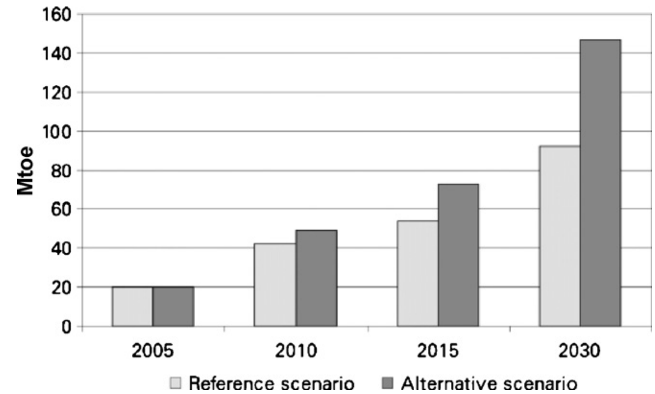

Fig. 1. Predicted biofuel production 2005–2030. *Source:* IEA (2006:394-395).

In India it is an astonishing fact that blending of 5% biodiesel fuel to the diesel fuel can save about Rs. 4000 crore every year. It is estimated that India will be able to produce 288 metric tonnes of biodiesel by the end of 2012, which will supplement 41.14% of the total demand of diesel fuel consumption in India. The cost of biodiesel and demand of vegetable oils can be reduced by non-edible oils, instead of vegetable oil but India is not self-sufficient in edible oils. Therefore, there is a need to find alternate feedstocks. In order to explore additional oil resources, research work has been undertaken for screening of non-traditional oil seeds for their potential as biodiesel feedstock.

The main resources for biodiesel production can be non-edible oils obtained from plant species such as *Jatropha curcas* (ratanjyot), *Pongamia pinnata* (karanj), *Ricinus communis* (castor), *Cerbera odollam* (sea mango), *Hevea brasiliensis* (rubber tree), *Calophyllum inophyllum* (polanga), *S. chinensis* (jojoba), *Madhuca indica* (mahua) and *Thevettia peruviana* (yellow oleander), etc. [5]. This paper provides information about current energy scenario in India, significance of non-edible oil over edible oils and presents status and utilization of non-edible feedstocks. This paper also focuses on biology, distribution and chemistry of selected non-edible biodiesel feedstocks.

2. Energy scenario in India

India's population of more than 1028 million is growing at an annual rate of 1.58% and has resulted in more energy use. As fossil fuel energy becomes scarcer, India will face energy shortages

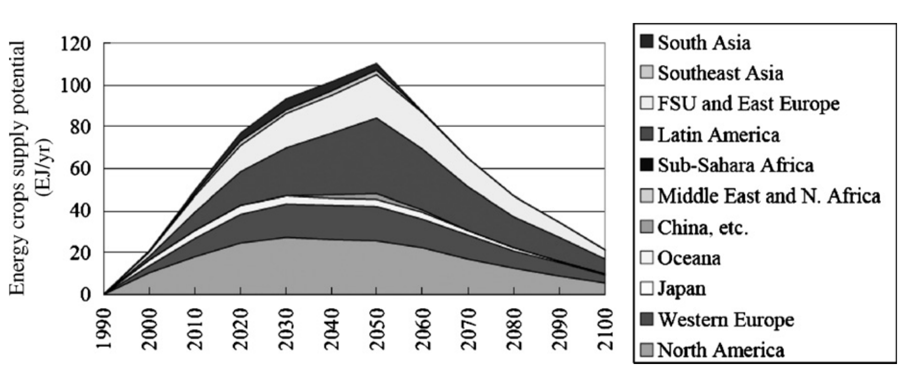

Fig. 2. Supply potential of energy crops [4].

significantly due to increase in energy prices and energy insecurity within the next few decades [6]. India is one of the fastest growing economies in the world and energy is a critical input for socio-economic development. The developmental objectives focus on economic growth, equity and human well being. India's energy security would remain vulnerable until alternative fuels to substitute or supplement petro-based fuels are developed based on indigenously produced renewable feedstocks. Furthermore, energy strategy of a country aims at efficiency and security and to provide access which being environment friendly and achievement of an optimum mix of primary resources for energy generation [7]. According to a report released by Greenpeace on March 24, 2009 in New Delhi, renewable energy can successfully meet over 35% of power demand in India by 2030, and half of the forecasted energy needs can be met just by efficient and judicious production, distribution and use of energy. The development of energy infrastructure is going to be strong in India. Thus, there is a huge opportunity lying ahead in the field of renewable energy in India. Furthermore, green energy revolution will not only help in saving money and sustain global economic development, but also facilitate to deal with the catastrophe of climate change [8].

Biofuels are eco-friendly fuels and their utilization would address global concerns about containment of carbon emissions. India has a ray of hope in providing energy security through development of biofuel. The Indian approach towards the biofuels, in particular, is somewhat different to the current international approaches which could lead to conflict with food security. It depends solely on non-food feedstocks to be raised on degraded/marginal or wastelands that are not suited to agriculture, thus avoiding a possible conflict of fuel vs. food security. Moreover, in the future, second generation biofuels could use agricultural residues and other feedstocks that are not used as food or feed. Feedstock costs comprise more than half the costs of producing both ethanol and biodiesel. The development and use of biofuels has not been commercially viable without significant government support. In Indian context, the National Policy on Biofuel has been prepared by the Ministry of New and Renewable Energy (MNRE), which is the body governing the usage of renewable energy resources. MNRE targets a 20% blending of biofuels such as bioethanol and biodiesel with the fossil-derived mineral fuel by 2017 [9]. It thus becomes imperative to search for potential non-edible feedstocks and their appropriateness for biodiesel synthesis.

3. Need for non-edible oil seeds crop as biodiesel feedstock

A considerable amount of research has been done on alternative feedstocks for biodiesel production all over the world. There are large numbers of edible and non-edible plant species for which engine tests and physico-chemical laboratory test have already been conducted. In contrast to edible oil, non-edible oils like jatropha, castor, karanj, rubber seed and sea mango are not suitable for human consumption due to the presence to toxic compounds in the oil. The seed of *P. pinnata* contains pongam oil which is bitter and non-edible with disagreeable taste due to the presence of flavonoid constituent, pongamin and karajin. This seed is usually used as fish poison [10]. The cost of plantation in terms of per kg oil for non-edible oil crops is lower than the plantation cost for edible oil crops, with an exception for palm oil.

The existing potential for tree borne oilseeds in India is 3.0–3.5 million tonnes, but the collection of only 0.5–0.6 million tonnes is being realized. In India, use of edible oils for biodiesel production is not practicable because of the big gap in demand and supply of edible oils. Furthermore, wide-scale production of crops for biodiesel feedstock can cause an increase in worldwide food and commodity prices. Increased pressure to augment production of edible oil has also put limitations on the use of edible oils for production of biodiesel. In Indian conditions, only such plant sources can be considered for biodiesel, which produce non-edible oil and can be grown in large scale on non-cropped marginal and wastelands. India hopes to convert "marginal lands" and to employ surplus agricultural labor to produce the non-edible oil required for biofuel production [11].

4. Potential non-edible biodiesel feedstock in India

Subramanian et al. [12] reported that there are over 300 different species of trees which produce oil bearing seeds. Thus, there is a significant potential for non-edible oil source from different plants for biodiesel production as an alternative to petro-diesel. Work reported by Azam et al. [13] on various oil bearing plant species in India reveals various species that are unutilized and have the potential to be used as raw materials for biofuel production. Out of the 75 species studied, 37 species were found to be suitable for biodiesel development as they could meet norms of internationally accepted ASTM standards.

The potential of all these species can be exploited, depending on their techno-economic viability for production of biofuels. The main commodity sources for biodiesel production from the non-edible oils can be obtained from plant species, such as *J. curcas* (ratanjyot), *P. pinnata* (karanj), *C. inophyllum* (nagchampa), *R. communis* (castor), *Argemone mexicana* (Mexican prickly poppy), *C. odollam* (sea mango), *Putranjiva roxburghii* (Lucky bean tree), *Sapindus mukorossi* (soapnut), *H. brasiliensis* (rubber tree), *C. inophyllum* (polanga), *Melia azedarach* (syringa), *S. chinensis* (jojoba), *M. indica* (mahua), *Schleichera triguga* (kusum), and *T. peruviana* (yellow oleander), etc. They are easily available in many parts of the world and are very cheap compared to edible oils in India [14]. Tables 1 and 2 summarized the yield potential and fatty acid composition in oils of selected non-edible feedstocks [13–26]. In next section, we will evaluate these non-edible oil seed crop species as biodiesel feedstocks on the basis of information available in literature about their distribution, biology and chemistry. In Fig. 3 we have tried to show photographs of different non-edible fruits for morphological identification.

Table 1
Estimated yield of non-edible oil seeds plants.

Scientific name	Plant type	Plant part	Oil yield (kg/ha)	References
Azadirachta indica (Neem)	Tree	Seed	2670	Nabi et al. [15]; Azam et al. [13]
Calophyllum inophyllum (Polanga)	Tree	Seed	4680	Azam et al. [13]
Hevea brasiliensis (Rubber)	Tree	Seed	40–50	Ramadhas et al. [16]
Jatropha curcas (Physic nut)	Tree/shrub	Seed	1900–2500	Duke [17]
Pongamia (Millettia) *pinnata*/*Pongamia glabra* (Koroch, karanja)	Tree	Seed	225–2250	Karmee and Chadha [14]
Ricinus communis (Castor)	Tree/shrub	Seed	450	FAOSTAT [18]; Duke [17]
Simarouba glauca (Paradise tree)	Tree	Seed	900–1200	Dash et al. [19]
Thevetia peruviana (Yellow oleander)	Shrub	Seed	1575	Balusamy and Marappan [20]

Table 2
Fatty acid compositions of some selected non-edible seed oil.

Item	Sources	Fatty acid composition (%)	References
1.	*Argemone mexicana*	14:0 (0.8), 16:0 (14.5), 18:0 (3.8), 18:1 (18.5), 18:2 (61.4), 20:0 (1.0)	Hilditch and Williams [21]
2.	*Calophyllum inophyllum* Linn	16:0 (17.9), 16:1 (2.5), 18:0 (18.5), 18:1 (42.7), 18:2 (13.7), 18:3 (2.1), 24:0 (2.6)	Bringi [22]
3.	*Jatropa curcas* Linn	14:0 (1.4), 16:0 (15.6), 18:0 (9.7), 18:1 (40.8), 18:2 (32.1), 20:0 (0.4)	Bringi [22]
4.	*Madhuca indica* JF Gmel	14:0 (1.0), 16:0 (17.8), 18:0 (14.0), 18:1 (46.3), 18:2 (17.9), 20:0 (3.0)	Singh and Singh [23]
5.	*Melia azadirach* Linn	14:0(0.1), 16:0 (8.1), 16:1 (1.5), 18:0 (1.2), 18:1 (20.8), 18:2 (67.7)	Hilditch and Williams [21]
6.	*Pongamia pinnata* Pierre	16:0 (10.6), 18:0 (6.8), 18:1 (49.4), 18:2 (19.0), 20:0 (4.1), 20:1 (2.4), 22:0(5.3), 24:0 (2.4)	Bringi [22]
7.	*Putranjiva roxburghii*	14:0 (0.03), 16:0 (10.23), 16:1 (0.07), 17:0 (0.07), 17:1 (0.02), 18:0 (10.63), 18:1 (48.65), 18:2 (27.50), 18:3 (0.87), 20:0 (1.05), 20:1 (0.30), 22:0 (0.24), 22:1 (0.03), 24:0 (0.31).	Halder et al. [24]
8.	*Thevetia peruviana* Merrill	16:0 (15.6), 18:0 (10.5), 18:1 (60.9), 18:2 (5.2), 18:3 (7.4), 20:0 (0.3), 22:0 (0.1).	Saxena and Jain [25]
9.	*Schleichera triguga*	12:0 (0.31), 14:0 (15.54), 16:0 (10.35), 18:0 (11.11), 18:1 (27.08), 18:2 (6.14), 20:0 (15.79), 20:1 (6.17), 20:2 (0.08), 22:0 (0.01)	Sharma and Singh [26]

4.1. Biology, distribution and chemistry of selected non-edible biodiesel feedstock

The identification of high biomass yielding perennial non-food feedstocks that can be grown using low inputs on marginal lands is recommended by Indian government. Such feedstocks offer opportunities to rehabilitate wastelands. The key factor to decide the suitability of a feedstock for biodiesel production is their adjustment to particular soil type and oil yield. The crops with higher oil yield are more preferable in the biodiesel industry because it can reduce the production cost. Generally the cost of raw materials accounts about 70–80% of the total production cost of biodiesel. In some case costs of the non-edible oils cannot be determined as they are currently not traded in the open market. Among the non-edible biofuel crop *Jatropha* was found to give the highest yield. This is followed by *P. pinnata* and castor. However, the oil yield in *P. pinnata* is not stable, depending on many factors such as plantation and oil extraction technique of the oil crops. On the other hand, the low plantation cost for castor and *P. pinnata* compared to the rest is basically because these two plants require very minimum fertilizer and irrigation.

4.1.1. J. curcas L. [family: Euphorbiaceae; common name: tropical physic nut, ratanjyot]

Jatropha a multipurpose, drought resistant plant, widely distributed in the wild or semi-cultivated areas in Central and South America, Africa, India and South East Asia [27,28] with many attributes and has considerable potential for biodiesel production. *Jatropha* is well adapted to arid and semi-arid conditions. In low rainfall areas and in prolonged rainless periods, the plant sheds its leaves as a counter to drought. Since flowers of *Jatropha* are developed terminally, the plants with good ramification after pruning can produce many fruits. Also the pruning of the plants keep them low enough to facilitate the harvest of the fruits, because the time needed to harvest a certain number of kg of seeds, is a very important factor of the economic feasibility of *Jatropha* oil

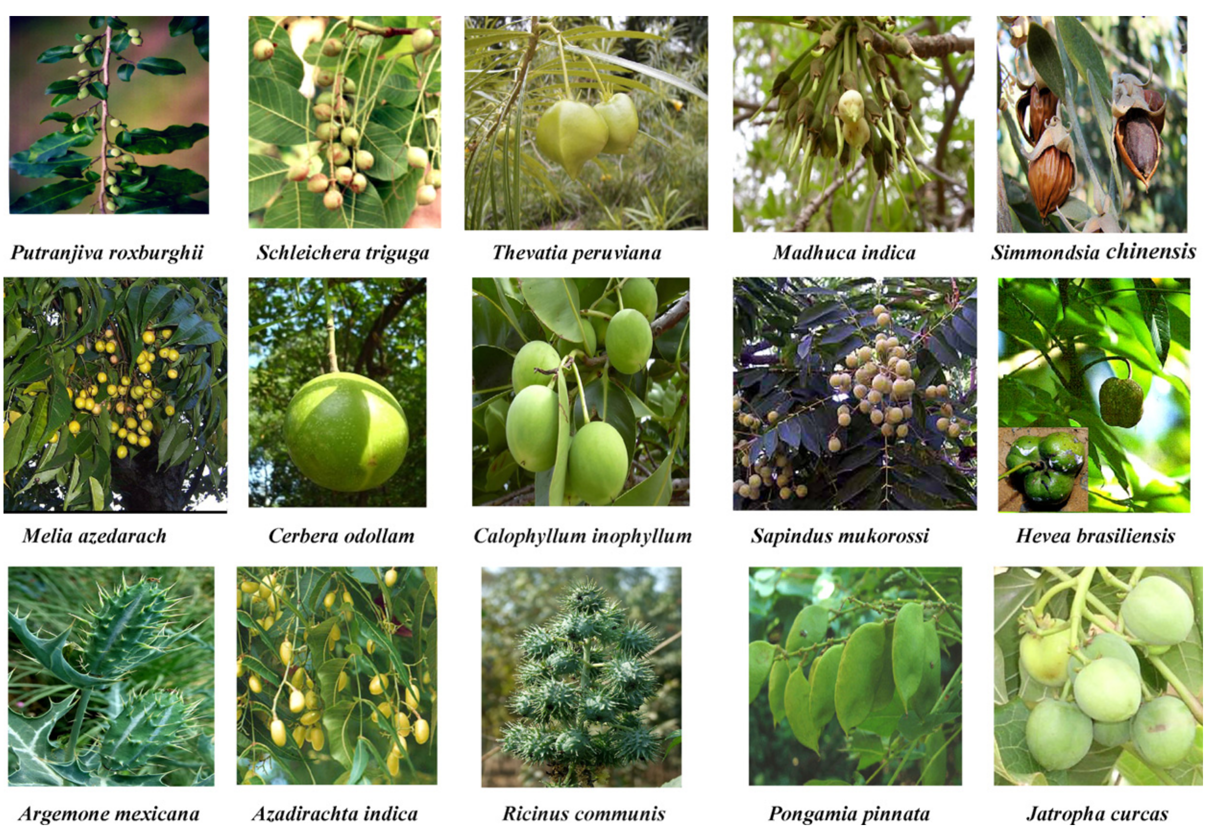

Fig. 3. Selected non-edible fruits bearing plants.

production [29]. Despite the interest in *Jatropha* the available yield performance data for this plant species are limited and somewhat uncertain. However, in different countries and regions the seed yield of *Jatropha* ranges from 0.1 to 15 tonnes/ha/year [30]. Efforts were made by different researchers to increase its yield under drought and salt stress conditions [31–33]. The presence of antinutritional factors is also likely to increase the shelf-life of the seeds. Depending on the variety, the decorticated seeds contain 40–60% of oil, which is used for many purposes such as lighting, as lubricant, for making soap and more importantly for biodiesel production. The seeds of *J. curcas*, in general, are toxic to humans and animals [29].

Jatropha is rich sources of hydrocarbons and have created interest all over the world for the use of its seed oil as a commercial source of fuel [34,35]. The kernels of *Jatropha* yield 46–58% of semidry oil (iodine value 93–107) and contain mainly oleic (37–63%) as principal fatty acid unlike other *Jatropha* species, which show predominance of linoleic acid. Jatropha produces an oil quality rich in oleic (42%) and linoleic (35%) acid and smaller amounts of palmitic (14%) and stearic acid (6%) [29]. Fatty acid composition could be altered to some extent through interspecific hybridization. However, a more targeted approach would be to silence the delta-9 or 12 desaturase genes for increased accumulation of stearic or oleic acids, respectively as done in other oilseed crops [36].

4.1.2. *P. pinnata (L.) Pierre [family: Fabaceae – Papilionoideae; common name: karanj/pungam]*

Karanja is a medium-sized tree with a short crooked trunk and a broad crown of spreading or drooping branches [37]. It has been introduced to humid tropical lowlands in the Philippines, Malaysia, Australia, the Seychelles, the United States of America and Indonesia [38]. The natural distribution of karanj is along coasts and river banks in India and Myanmar. *Pongamia* is native to humid and subtropical environments, thrives in areas having an annual rainfall ranging from 500 to 2500 mm. *Pongamia* is important for shade, ornamental value, seed oil, plant fodder and green manure. *P. pinnata* is currently cultivated mainly for ornamental purposes due to its large canopy and showy flowers. The different parts of the plants like leaves, roots and flowers are reported to possess medicinal properties (WOI, 1969). It is one of the few nitrogen fixing trees that produce seeds with a significant oil content has been receiving considerable attention ever since its role as a feed stock for biodiesel production [39–42]. *Pongamia* seeds are heavy, contain greater food reserves (Athaya, 1985a) and around 800–1200 seeds are equivalent to weigh 1 kg. Shivanna et al. [43] reported significant differences among the sources for seed and seedling traits on the basis of evaluation of eight seed sources. Seed length varied from 0.77 to 1.11 cm and seed width from 0.69 to 0.92 cm, 100 seed weight varied from 19.80 to 32.20 g. Mukta et al. [44,45] reported variability for 100 seed weight (39.8–229.5 g) and seed oil content (9.5–46%) among the 75 accessions collected by them from four districts of Andhra Pradesh, India. Kaushik et al. [46] also observed variability in oil content from 32.6% to 44% in accessions collected from Haryana state. *Pongamia* exhibits wide adaptation to various soil types and saline/alkaline conditions and is regarded as a drought tolerant species [47]. *Pongamia* tree can be planted in degraded lands, wastelands, or fallow lands and is highly tolerant to salinity. However, highest growth rate and yield of oil are observed on well-drained soils with assured moisture [48]. *P. pinnata* is nitrogen fixing plant and can be cultivated on land which has been exhausted of nutrients due to long duration of plantation. It plays an important role to help to improve the soil quality so that the exhausted land can be reused for agricultural purpose in future. Variability for fatty acid profile has been recorded and selection of genotypes with optimum values for biodiesel traits viz. saponification number, iodine value and cetane number has been reported [44,45]. These properties support the suitability of this plant for large-scale vegetable oil production required by a sustainable biodiesel industry. The future success of *P. pinnata* as a sustainable source of feedstock for the biofuels industry is dependent on an extensive knowledge of the genetics, physiology and propagation of this legume. In particular, research should be targeted to maximizing plant growth as it relates to oil biosynthesis [49].

4.1.3. *R. communis [family: Euphorbiaceae; common name: castor]*

Castor, a drought resistant plant and believed to be originated in Abyssinia. It is distributed throughout tropical and subtropical regions, and is well adapted to the temperate regions. The major castor producing countries are India, China, Brazil, USSR, and Thailand, while the major importing countries are the USA, USSR and Japan. According to FAOSTAT [50], India is the leading producer of castor in the world (60% of the total production) with an annual production of about 0.73 Mt. In ecological requirements it has similarity with *jatropha*. Castor is currently cultivated on commercialized scale for the seeds and oils which are used in textile, printing industry, in the manufacturing of high-grade lubricants and also in traditional medicine [51]. According to Lele [52], income generate from plantation of jatropha for first 2–3 years is very low. Therefore, castor can be intercropped to obtain income for that initial duration because castor can give higher production yield in a shorter period than *jatropha*. This would help to improve economical viability of both jatropha and castor plantation on a commercial scale. Castor oil has the most unique composition with approximately 89.5% ricinoleic acid. Ricinoleic acid is also known as castor oil acid, an unsaturated fatty acid which is soluble in most organic solvents. The phytotoxin present in castor plant is ricin, a water soluble protein which is concentrated in the seeds [53]. Among the vegetable oils, castor oil is distinguished by its high content (over 85%) of the hydroxylate fatty acid, ricinoleic acid (D-12-hydroxyocta-dec-cis-9-enoic acid). It is the only source of an 18-carbon hydroxylated fatty acid with one double bond [54]. Castor oil has various attributes i.e. unsaturated bonds, high molecular weight (298), low melting point (5 °C), very low solidification point (−12 °C to −18 °C), that make it industrially useful (www.castoroil.in). Despite the high viscosity of raw castor oil, the kinematic viscosity of transesterified castor oil is comparable to other vegetable oils making it suitable as a biodiesel blend. Castor oil is the only oil that is soluble in alcohol, and does not require heat and the consequent energy requirement of other vegetable oils in transforming them into fuel [55]. The other properties are low sulphur content (0.04%), ash content of 0.02%, negligible potassium, heating value of 39.5 GJ/t, iodine value of about 80 and flash point of 260 °C [51]. Castor sequesters 34.6 tonnes of CO_2/ha and has good carbon trading potential. The isolation of a natural mutant of castor bean recently with high oleic acid and low ricinoleic acid concentration diversifies potential uses for castor oil [56]. Moreover, genetic engineering of castor through silencing of the fatty hydroxylase gene which is responsible for conversion of oleic acid to ricinoleic acid leads to accumulation of high levels of oleic acid which would be of interest for the biodiesel market [56,57].

4.1.4. *Argemone mexicana L. [family: Papaveraceae; common name: Mexican prickly poppy]*

A. Mexicana is a species of poppy found in Mexico and now widely naturalized in the United States, India and Ethiopia. An annual herb with bright yellow sap, it has been used by the Natives of the western US and parts of Mexico. The seed-pods secrete a pale-yellow latex substance when cut open. This argemone resin contains berberine and protopine, and is used medicinally as a sedative. The non-edible seed plant like *A. mexicana* found everywhere

as weed has been found most suitable for biodiesel purpose. The plant prefers light (sandy) soils, requires well-drained soil and can grow in nutritionally poor soil. All parts of the plant, including the seed, contain toxic alkaloids [58] but it has many medicinal usages and can be apply in external part of body. The whole plant is analgesic, antispasmodic, possibly hallucinogenic and sedative [59–62]. The seeds contain 22–36% of a pale yellow non-edible oil, called argemone oil or katkar oil, which contains toxic alkaloids the sanguinarine and dihydrosanguinarine. The fatty acids present in *A. mexicana* seed oil are myristic acid, palmitic acid, stearic acid, oleic acid, linoleic acid and arachidic acid [13]. This crop does not exert any pressure on the agriculture land and can be grows in the waste land and infertile land, which is not used for agriculture and this way it may give an profitability as a commercial waste land crop.

4.1.5. *C. odollam [family: Apocynaceae; common name: sea mango]*

C. odollam grows well in coastal salt swamps and creeks in south India and along riverbanks in southern and central Vietnam, Cambodia, Sri Lanka, Myanmar, Madagascar and Malaysia [63,64]. The *C. odollam* tree grows to a height of 6–15 m and has dark green fleshy lanceolate leaves. The large white flowers have a delicate perfume, reminiscent of jasmine. The fruit, when still green, looks like a small mango, with a green fibrous shell enclosing an ovoid kernel measuring approximately 2 cm × 1.5 cm and consisting of two cross-matching white fleshy halves. On exposure to air, the white kernel turns violet, then dark grey, and ultimately brown or black. The plant as a whole yields a milky white latex [65]. Sea mango tree is a well-known 'suicide tree' because of its highly poisonous nature and toxic content in the seed is transferred into the oil after the extraction process. Many parts of the tree are used for the manufacture of fibre. The latex is known in India for its emetic, purgative and irritant effects [66]. The kernel contains the active glycosides cerberin, cerberoside and odollin [65–67]. The leaves and fruits of sea mango contain the potent cardiac substance (a glycoside) called cerberin, which is extremely poisonous if ingested [63]. The toxin (cerberin) can be easily separated out from the extracted oil by decantation and favoured the potential of its oil to be used as biodiesel feedstock. On the basis of extraction process, the oil extracted from *C. odollam* seeds was 54%. This value is similar to those of palm oil which stands at 45–50%, indicating that it can be a promising source of oil for biodiesel production [65]. The fatty acid composition of *C. odollam* oil is mainly oleic (48.1%), followed by palmitic (30.3%), linoleic (17.8%) and stearic (3.8%). The free fatty acid content in *C. odollam* oil is significantly higher than in palm oil. However, due to the high free fatty acid content in *C. odollam* oil, very specific catalyst is required for the transesterification process and to make the whole process commercially feasible.

4.1.6. *P. roxburghii [family: Euphorbiacae; common name: Lucky bean tree]*

Putranjiva tree belongs to the family Euphorbiacae of order Geranials which was identified by Roxburgh and accordingly the plant is called as *P. roxburghii*. In the Tropic of Cancer, these plants are abundantly available. Million tonnes of seeds of Putranjiva oil go to waste annually which villagers in remote areas can use pure Putranjiva, diesel oil blends to operate engines for running irrigation pumps, grinding mills or straw choppers for cattle feed for shorter duration at the time of fuel crisis or emergency period. Putranjiva oil is yellow in colour, highly pungent, volatile and rich in oleic acid. The compositions of oil are C14:0; 0.03%, C16:0; 10.23%, C16:1; 0.07%, C17:0; 0.07%, C17:1; 0.02%, C18:0; 10.63%, C18:1; 48.65%, C18:2; 27.50%, C18:3; 0.87%, C20:0; 1.05%, C20:1; 0.30%, C22:0; 0.24%, C22:1; 0.03%, and C24:0; 0.31%. The viscosity of this oil is 37.6 cSt at 40 °C whereas at 100 °C the viscosity is 9.8 cSt. At high temperature the viscosity comes to below 10 cSt which reduce the atomization problem. Therefore preheating of high viscous vegetable oil before fuel injection is the best way to use in diesel engine without any modification. According to Halder et al. [24], the pure vegetable non-edible oil, *P. roxburghii* can be used as an alternative diesel fuel of diesel engine without any modification of engine in the rural areas during fuel crises.

4.1.7. *S. mukorossi [family: Sapindaceae; common name: soapnut]*

Soapnut is a fruit of the soapnut tree generally found in tropical and subtropical climate areas in various parts of the world including Asia, America and Europe. It is reported that *S. mukorossi* species of soapnut grows wild from Afghanistan to China, ranging in altitudes from 200 to 1500 m in regions where precipitation varies from 150 to 200 cm/year [68]. Two main varieties (*S. mukorossi* and *S. trifoliatus*) are widely available in India, Nepal, Bangladesh, Pakistan and many other countries. Ucciani et al. [69] reported that the oil content in *S. trifoliatus* which is very similar to *S. mukorossi* seed kernels was on average 51.8% of seed weight. The plant grows very well in deep loamy soils and leached soils so cultivation of soapnut in such soil avoids potential soil erosion. The soapnut tree can be used for multiple applications such as rural building construction, oil and sugar presses, and agricultural implements among others. Hence, integration of soapnut plantation along with community forestry would help to produce more seeds as potential sources to the biodiesel feedstock.

The oil from soapnut has been considered a non-edible oil having significant potential for biodiesel production from the material which otherwise is a waste material. Chhetri et al. [70] carried out a comprehensive study on the uses of various parts of the soapnut tree. Soapnut has several applications from medicinal treatments to soap and surfactant. Soapnut fruit shells have been in use as natural laundry detergents from ancient times for washing fabrics, bathing and traditional medicines. Mandava [71] reported that saponins from soapnut shells can be used for treatment of soil contaminants. Several other studies also showed that soapnut has a great potential as a natural surfactant for washing the soils contaminant with organic compounds [8,9]. The recorded external use of saponin does not cite any toxic effects on human skin and eyes [72]. These applications all make use of the pericarp shell and the seeds are usually waste. Hence, the use of soapnut seeds as a biodiesel source becomes the "waste-to-energy" scheme. Furthermore, planting soapnut trees in community forestry and in barren lands provides sink for carbon sequestration as well as feedstock for biodiesel production. Olsen [73] reported that the total value of exports of soapnut as medicinal use including other four species made up to 52% of the total non timber forest products export to India from Nepal. The totals of 32 non-timber forest products are exported with a total value of 8.1 million US dollar for the year 1997/1998. Recently it was reported that the glycerol, a by-product of biodiesel production, can be used to produce organic acids such succinic acids by bacterial fermentation [74]. Hence, the economics of biodiesel from soapnut oil can easily be realized on community scale as it can be integrated in the community forestry plan.

4.1.8. *H. brasiliensis [family: Euphorbiaceae; common name: rubber tree]*

H. brasiliensis is the primary source of natural rubber and the tree's sap-like extract (known as latex) can be collected and used in various applications [16]. It is distributed mainly in Indonesia, Malaysia, Liberia, India, Srilanka, Sarawak, and Thailand. The tree is growing up to 34 m in height and requires heavy rainfall and produces seeds weighing from 2 to 4 g that do not currently have any major industrial applications. The oil content of the seeds, which may contain up to 17 wt.% FFA, ranges from 40 to 50 wt.% and is high in unsaturated constituents such as linoleic (39.6 wt.%), oleic

(24.6 wt.%), and linolenic (16.3 wt.%) acids [16]. Other fatty acids found in rubber seed oil include saturated species such as palmitic (10.2 wt.%) and stearic (8.7 wt.%) acids. The physical properties of the resultant rubber seed oil methyl esters include CP and PP values of 4 °C and −8 °C, respectively, and a kinematic viscosity (40 °C) of 5.81 mm^2/s [16].

4.1.9. C. inophyllum [family: Clusiaceae; common name: polanga]

Calophyllum is an ornamental, evergreen tree found in tropical regions of India, Malaysia, Indonesia, and the Philippines. It is growing up to 25 m in height, and produces a slightly toxic fruit that contains a single, large seed [75]. The oil obtained from polanga seeds is inedible and high in FFA content (up to 22 wt.%) and unsaturated species such as linoleic (38.3 wt.%) and oleic (34.1 wt.%) acids. The defatted meal, though it contains a good amount of protein, is not edible due to the presence of saponins which are toxic. The remaining fatty acids found in polanga oil are stearic (13.0 wt.%) and palmitic (12.0 wt.%) acids, and linoleic acid (0.3 wt.%) present in a trace amount. Physical properties of polanga oil methyl esters include CP and PP values of 13 °C and 4 °C, respectively, a flash point of 140 °C, and a kinematic viscosity (40 °C) of 4.92 mm^2/s. The exhaust emissions characteristics of methyl esters from polanga oil are summarized by Sahoo et al. [75].

4.1.10. M. azedarach [family: Meliaceae; common name: syringa or Persian lilac]

M. azedarach is a deciduous tree that grows between 7 and 12 m in height. It is native to India, southern China, and Australia. The oil content of dried syringa berries, which are poisonous, is around 10 wt.% [76]. Syringa oil is characterized by a high percentage of unsaturated fatty acids such as oleic (21.8 wt.%) and linoleic (64.1 wt.%) acids. Other constituents that are present in greater than 1 wt.% are saturated fatty acids such as palmitic (10.1 wt.%) and stearic (3.5 wt.%) acids [76]. Physical properties of biodiesel prepared from syringa oil include an IV of 127, a kinematic viscosity (40 °C) of 4.37 mm^2/s, and a specific gravity of 0.894 g/mL [76].

4.1.11. S. chinensis [family: Simmondsiaceae; common name: jojoba]

Simmondsia is a perennial shrub that is native to the Mojave and Sonoran deserts of Mexico, California, and Arizona. Jojoba is unique in that the lipid content of the seeds, vary between 45 and 55 wt.%, is in the form of long-chain esters of fatty acids and alcohols (wax esters) [77,78] as opposed to TAG. The fatty acid component of jojoba wax esters primarily consists of eiconenoic, erucic, and oleic acids with cis-11-eicosen-1-ol and cis-13-docosen-1-ol principally composing the alcohol component. As a consequence of the unique composition of jojoba wax, methanolysis affords a product that consists of a mixture of FAME and long chain alcohols, as the separation of these materials is problematic. The physical properties of this mixture do not compare favourably with biodiesel prepared from other feedstocks, as the CFPP value is 4 °C, and the kinematic viscosity (40 °C) is 11.82 mm^2/s [77]. Reduction of the alcohol component through laborious purification results in an improvement in CFPP to −14 °C; however, the kinematic viscosity (40 °C; 9.0 mm^2/s) remains considerably above accepted American (ASTM D6751) and European Union (EN 14214) limits. The reaction conditions for the production of biodiesel from jojoba wax esters have been optimized by RSM [77,78].

4.1.12. M. indica [family: Sapotaceae; common name: butter tree, mahua]

Mahua is a tropical tree (approximately 20 m in height) found largely in the central and northern plains and forests of India. It grows fast and possesses evergreen or semi-evergreen foliage, and is adapted to arid environments [79,80]. In India the two major species of *Madhuca* are *indica* and *longifolia*. *M. indica* is one of the forest based tree-borne non-edible oils with high production potential of about 60 million tonnes per annum in India [81]. Non-edible fruit contains one to two kidney-shaped kernels which are obtained from the tree in 4–7 years [82] and continues up to 60 years. The yield of *M. indica* seeds varies (5–200 kg/tree) depending upon size and age of the tree [83]. The kernel constitutes about 70% of the seed and contains 50% oil [79,84]. The oil has a relatively high percentage of saturated fatty acids such as palmitic (17.8 wt.%) and stearic (14.0 wt.%) acids. The remaining fatty acids are chiefly distributed among unsaturated components such as oleic (46.3 wt.%) and linoleic (17.9 wt.%) acids [85]. The relatively high percentage of saturated fatty acids (35.8 wt.%) found in mahua oil results in relatively poor low-temperature properties. The mahua oil generally contains about 20% FFAs and a procedure for converting this mahua oil to biodiesel is very much required.

4.1.13. S. triguga [family: Sapindaceae; common name: kusum]

Kusum is a medium or large sized dense tree growing to 35 to 45 ft in height. The major kusum producing nations are India, Myanmar, Sri Lanka, Timor and Java. In India it mainly occurs in sub-Himalayan tracts in the north, central parts of eastern India, particularly in Orissa. Its oil has various uses like in medicines, hair dressing and for soap manufacture. The flowers come from February to April and yields fruit in June and July. The fruits are smooth, hard skin berries contains one or two irregularly ellipsoidal slightly compressed seeds. The kernel is U shaped and seed coat is brown. Most members of the Sapindaceae family contain cyanogenic compounds in the kernel and presence of cyanolipids makes kusum oil toxic and bitter in taste (non-edible). The cyanogenic compounds can be present in the concentration of 0.03–0.05% as hydrogen cyanide (HCN). Production potential of kusum oil is 66,000 tonnes per year in India, out of which 4000–5000 tonnes are collected. The oil content is 51–62% but the yields are 25–27% in village ghanis and about 36% oil in expellers. It contains only 3.6–3.9% of glycerin while normal vegetable oil contains 9–10% glycerine. FFA (free fatty acid) present in oil is 5–11%. The oil can be used as substitutes of diesel but, kusum oil has problem of viscosity. The work of Sharma and Singh [26] showed the successful use of kusum for biodiesel synthesis with high yields and conversion. They also recommended that as it contains hydrogen cyanide, biodiesel synthesized from kusum may posses HCN and may get emitted on usage in the exhaust of CI engines. Hence, the exhaust emission coming from kusum oil biodiesel has to be analysed and if it emits cyanide, its pre-treatment would be necessary. An extensive study dealing with this aspect becomes necessary prior to the usage of biodiesel derived from kusum.

4.1.14. T. peruviana [family: Apocynaceae; common name: yellow oleander]

Thevettia is an evergreen perennial shrub reaching a height of 4.5–6 m with deep green linear sword-shaped leaves and funnel shaped (yellow, white or pinkish yellow coloured) flowers. It is a native of tropical America especially Mexico, Brazil and West Indies and has naturalized in tropical regions of the globe. It is known by various common names as yellow oleander (nerium), gum bush, bush milk, exile tree in India, cabalonga in Puerto Rico, ahanain Guyana, olomi ojo by Yorubas in Nigeria. The plant starts flowering after one and a half year and after that it blooms thrice a year [20]. *Thevetia* plants produce more than 400–800 fruits yearly depending on the rainfall and plant age [86]. Almost all parts of the plant are poisonous and bear white coloured latex. The number of kernels per fruit and the oil yield are significantly different among geographical locations. Although, it has high oil content (67%) in its kernel [13] and favourable protein content (37%) in de-oil cake [87], but it has remained only an ornamental or fencing or wasteland plant. Seed

coat and seed wing contains semi-oily material around 8.41% and 2.01%, respectively. The shell contains some hexane soluble material (0.36%). So the shell should be separated before oil expulsion. The plant has annual seed yield of 52.5 t h^{-1} and about 1750 L of oil can be obtained from a hectare of waste land [20]. Its kernel oil has a very good thermal stability and thus has a potential for various uses [87].

4.1.15. Azadirachta indica [family: Meliaceae; common name: neem]

Azadirachta can adapt itself in a wide range of temperature (49–0 °C). This tree is present in various countries like Asia, Africa, Central and South America. It grows almost in all types of soil including clay, saline, alkaline, dry, stony, shallow soils and even on solid having high calcareous soil. A mature tree can produce 30–50 kg of fruit every year and its life span is about 150–200 years. Hence there is a potential of about 540,000 tonnes of seeds, which can yield about 107,000 tonnes of oils and 425,000 tonnes of cake. But this large untapped source is only 25–30% utilized. This oil is light to dark brown in colour, bitter and has a great potential to make biodiesel for supplementing other conventional sources. This oil is mostly used in for preparing cosmetics, ayurvedic medicines and biopesticides. Crude neem oil generally contains high amounts of FFAs and a procedure for converting neem oil to biodiesel is very much required. Ilavarasi et al. [88] reported that crude neem oil with high FFA of 21.6 was pretreated with an acid catalyst and FFA were reduced to less than 1% and the reaction parameters for the two step process was optimized. This process gives an yield of 89% neem biodiesel which has comparable fuel properties with that of diesel and are within the limits of prescribed by American standards of biodiesel.

5. Biofuel and environmental concern

Assessing the long term environmental impact of biodiesel feedstocks production is a complex task. Moreover, clearing of land in favour of biofuel crops and the consequent loss of forests, peat lands and grasslands would actually aggravate global warming and climate change [89].

In view of environmental considerations, biodiesel is considered carbon neutral because all the CO_2 released during consumption had been sequestered from the atmosphere for the growth of oil crops. The combustion of biodiesel has reported to emit lesser pollutants in the environment compared to diesel [90]. This indicates that the engine exhaust contains no SO_2, and shows decreasing emissions of PAH, CO, HC, soot and aromatics. The NO_x emission is reported to be in less as compared to diesel depending on engines combustion characteristics. The practice of growing energy crops on marginal lands has become an important area of research, especially as concerns about food security and biodiversity mount.

Besides contributing to GHG emissions, biofuel-driven agricultural expansions can also lead to land-use conflicts among different stakeholders. Recently, Koh [91] investigated the potential habitat and biodiversity losses that may result from an increase in global biodiesel production capacity to meet future biodiesel demands (an estimated 277 million tonnes per year by 2050). Demand for biofuels and the resulting impact on food prices may further indirectly affect forests and biodiversity by undermining new incentive-driven systems for environmental conservation.

6. Future direction

Growing plants for biofuel production on limited available agricultural areas, will potentially increase food and fodder prices. This condition will be more prominent in the poorer countries and less developed agricultural areas. Taking all of these points in account, the only way out of this dilemma is to identify promising species and breed novel plants on abandoned marginal and degraded agricultural land to enhance their capacity to build up biomass. Promoting the cultivation of non-edible oil seed crop not only allow wasteland utilization but at the same time it also used to produce oil crops for biodiesel production without the need to compete with food crops for the limited arable land. Taking all these factors into consideration, non-edible oils definitely have the advantage over edible oils as biodiesel feedstock. An ideal solution would be an equal share contributed by edible oil and non-edible oil. Fertile agricultural land should remain for edible oil cultivation while wasteland or fallow land should be planted with non-edible oil crops that have simpler ecological requirements. This will allow optimum utilization of limited land areas especially in developed countries. Diversified resources for biodiesel feedstock will also ensure that the quality of biodiesel obtained is suitable within that particular region.

7. Conclusions

The demand for biodiesel worldwide is expected to increase sharply in the near future. Competition of edible oil sources as food vs. fuel makes edible oil not an ideal feedstock for biodiesel production. Although rush to energy crops, either food or non-food crops, threatens to cause food shortages and damage to biodiversity with partial benefits. Moreover, diversion of land from food or feed production to energy biomass production will influence food prices. India is now in the development stage of establishing large-scale feedstock production bases and modern biofuel production factories. We will have to focus our work primarily on the exploration of the alternative biodiesel feedstock particularly non-edible oil seeds to offer a number of environmental and socio-economic opportunities for India as well as world. Second priority is the establishment of biofuel production system which should have a steady, low-cost, and non-food feedstock supply and highly competent biofuel production technologies. Moreover, further research is needed to validate the promise of non-edible crop as a biodiesel feedstock.

Acknowledgement

Authors wish to thank Council of Scientific and Industrial Research, New Delhi, India for providing financial support.

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